Εισαγωγική στην Οπτική Απεικόνιση

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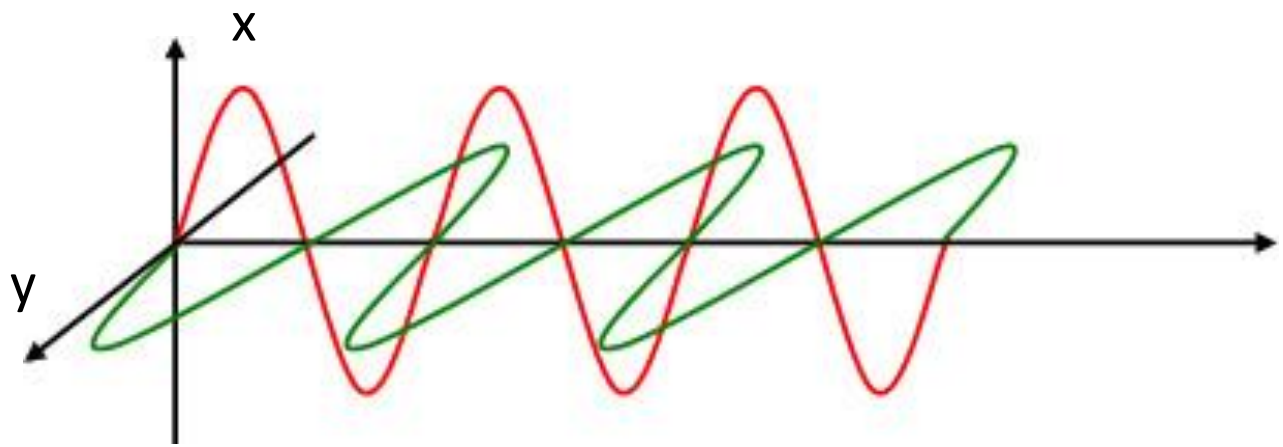
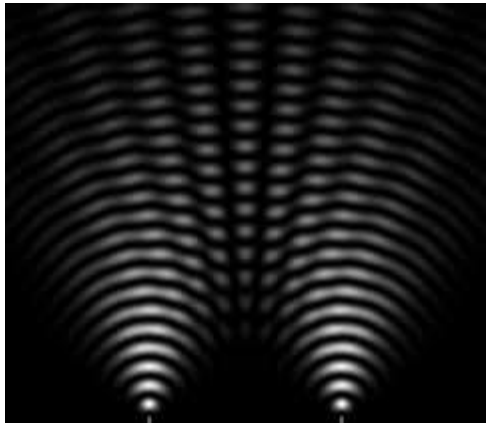
Light: A type of EM Radiation

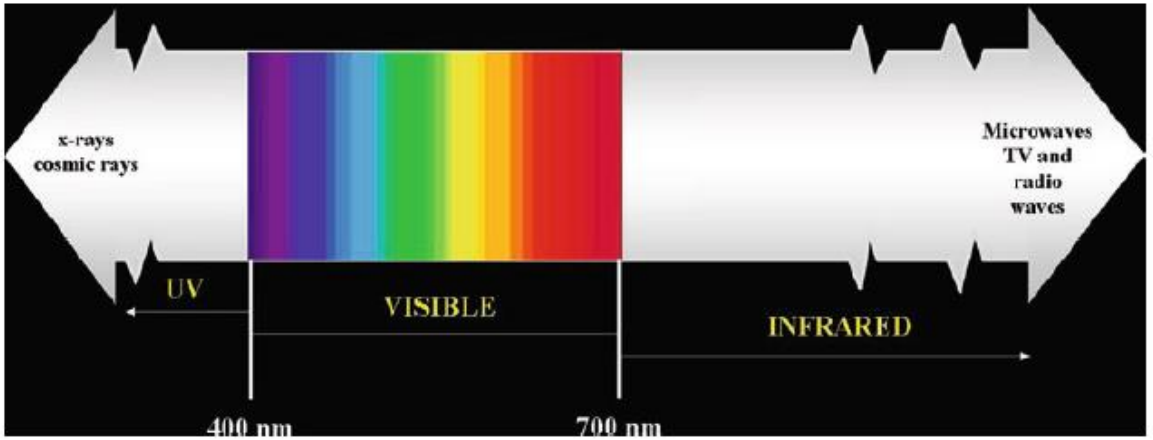
- EM radiation: electric and magnetic fields that vibrate on the plane (x-y) perpendicular to the axis of propagation (z)



Wave and Particle Descriptions of Light

- Light is a type of electromagnetic (EM) wave





- Light is composed of elementary particles (photons)
  - Energy of each photon depends on its wavelength λ

$$\mathrm{E} = h\nu = \frac{hc}{\lambda}$$

The (Idealized) Concept of Imaging

- Imaging systems: consist of lenses, mirrors, filters
- Ideal imaging system: map each point in the object onto a single point in the image

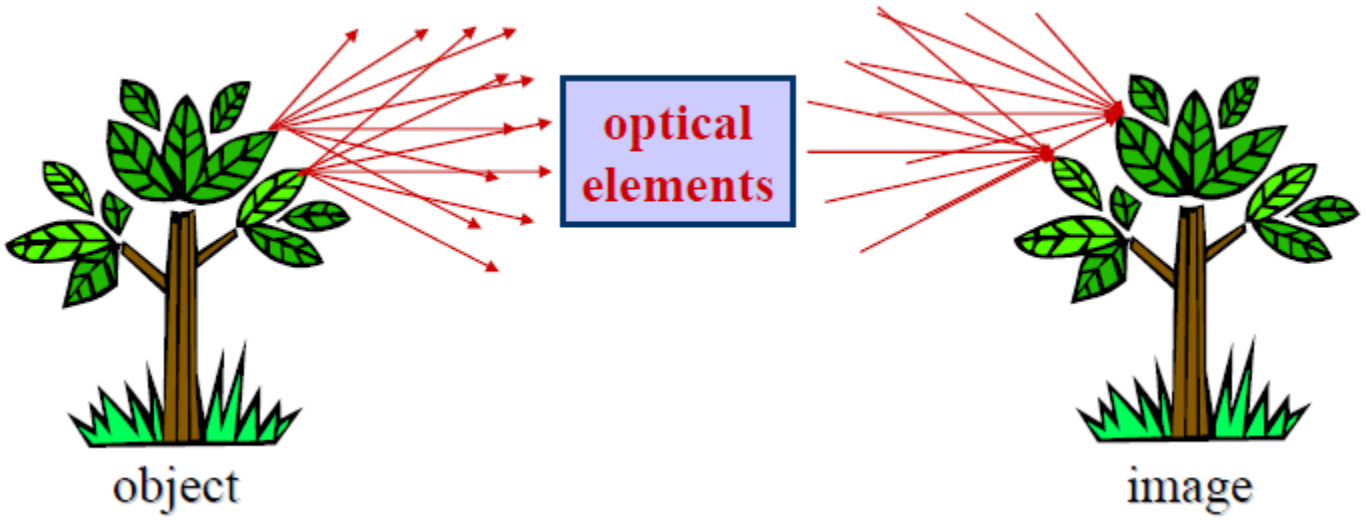
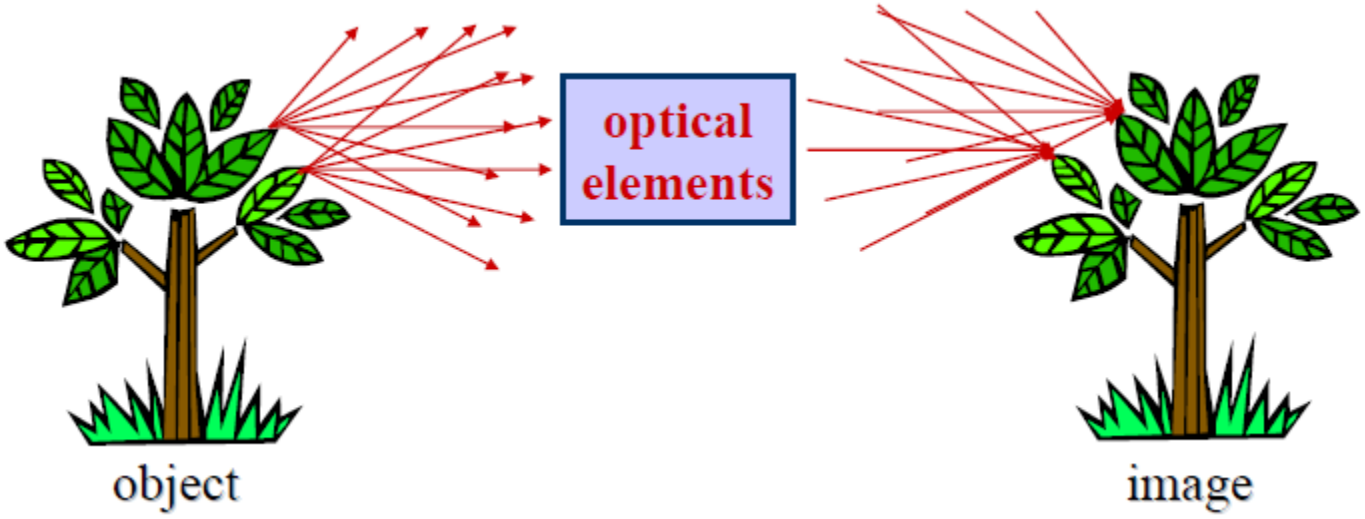


Image by G. Barbastathis, MIT

Imaging in Biological Sciences & Medicine

- Three major components



Sample types
- Cells, tissues

Emission types
- Fluorescence
- Darkfield, Phase imaging

Optical system
- Microscope
- Endoscope

Emission detection
- Detectors (CCD, PMT)
- Spatial sampling

Image by G. Barbastathis, MIT

3 Tools to Study Imaging Systems

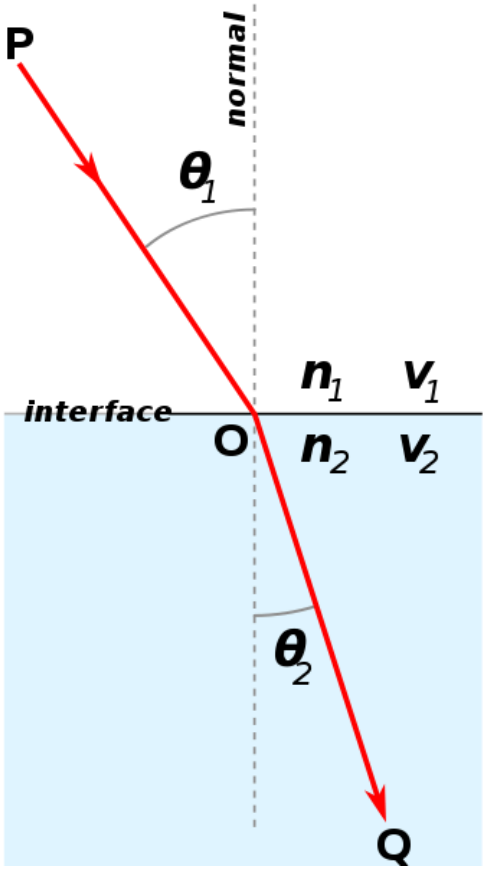
- Geometric Optics
- Diffraction theory → Point Spread Function
- Fourier Optics → Modulation Transfer Function

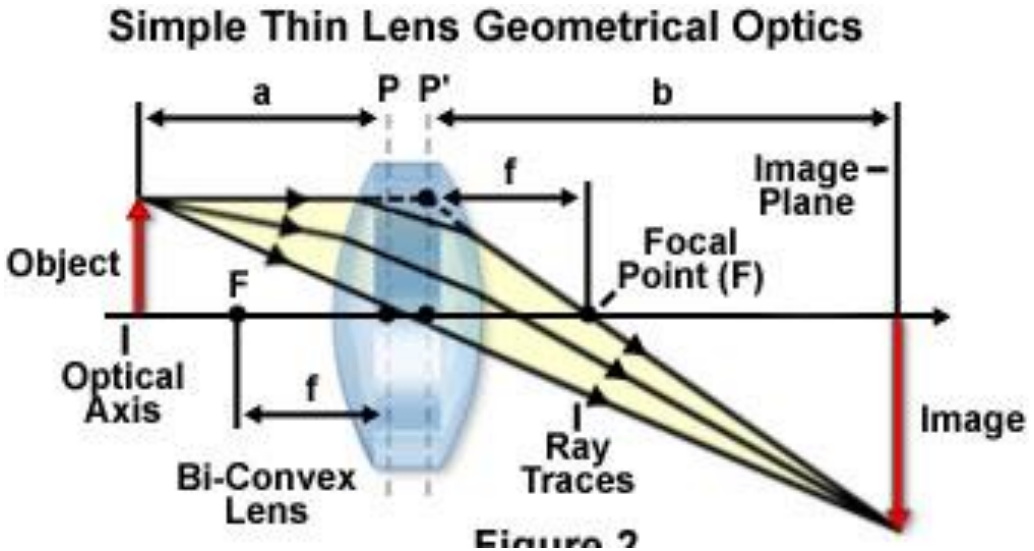
Geometric Optics

- Describe path of rays originating from each point of object
  - Utilize Snell's law of refraction

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

  - Follow paths of ray traces





http://www.olympusmicro.com/

Lens: The Simplest Optical System

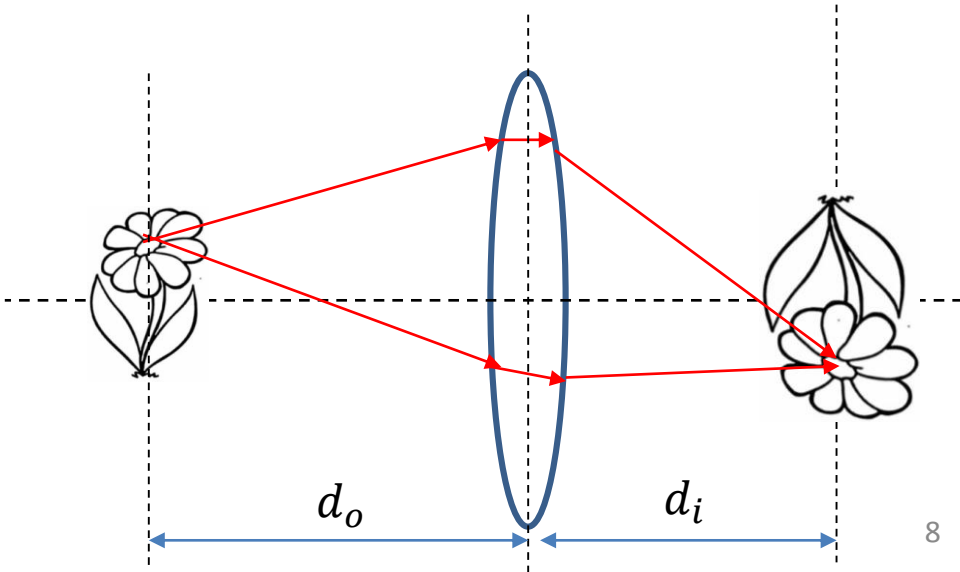
- The plane located d_o in front of the lens is imaged in a plane located d_i behind the lens such that

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

  - Where f is the focal length of the lens
  - The image is magnified by a factor of $M = \frac{d_o}{d_i}$
  - When $d_o \to f$, then $d_i \to \infty$

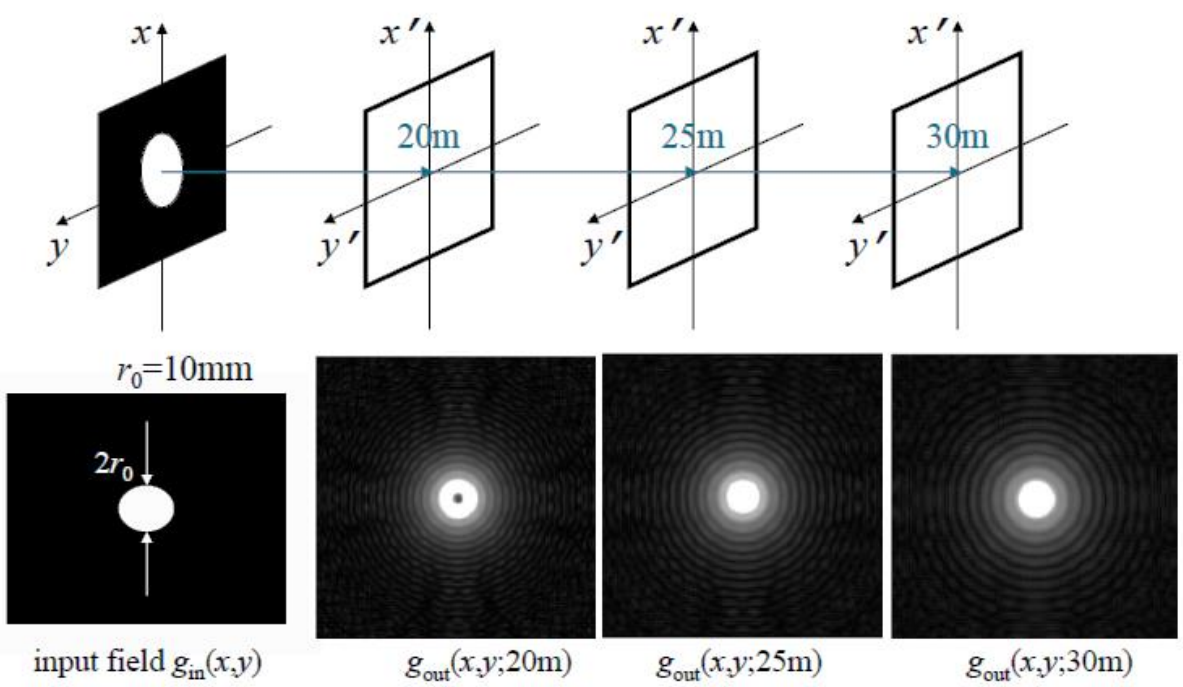
- The lens pupil diameter D controls amount of light collected by lens

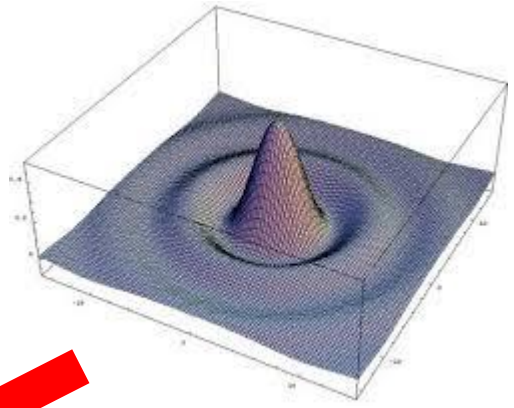
$$f\# = f/D$$



Diffraction (Περίθλαση)

- The wave nature of light affects light propagation in space
  - Described by the diffraction integral
- The following image shows diffraction by a circular slit



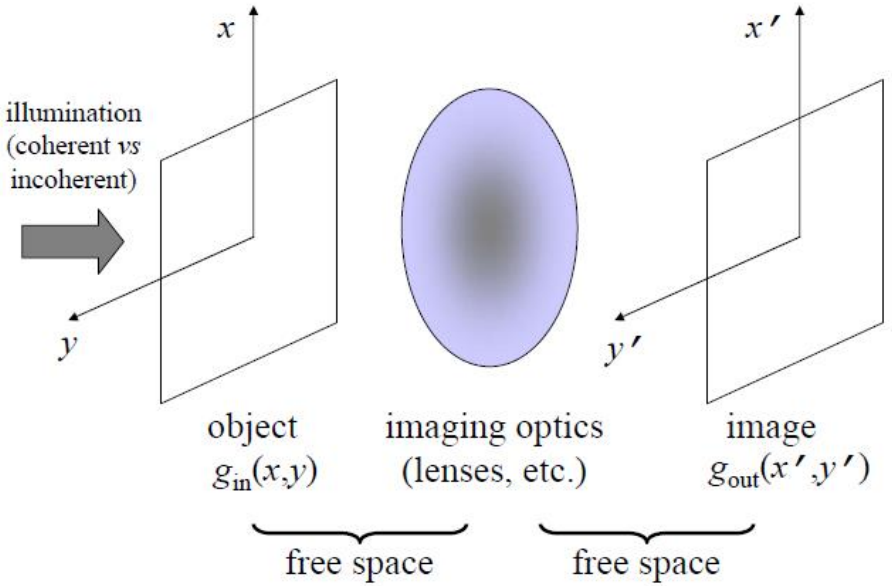


$$\mathrm{jinc}\left(\frac{2\pi r_0\sqrt{(x')^2+(y')^2}}{\lambda l}\right)$$

Images by G. Barbastathis, MIT

Optical System Response

- The response of an optical system
  - Describes how intensity@object plane is imaged to intensity@image plane
  - Can be described as a linear space-invariant system (2D corresponding of LTI dynamic systems)



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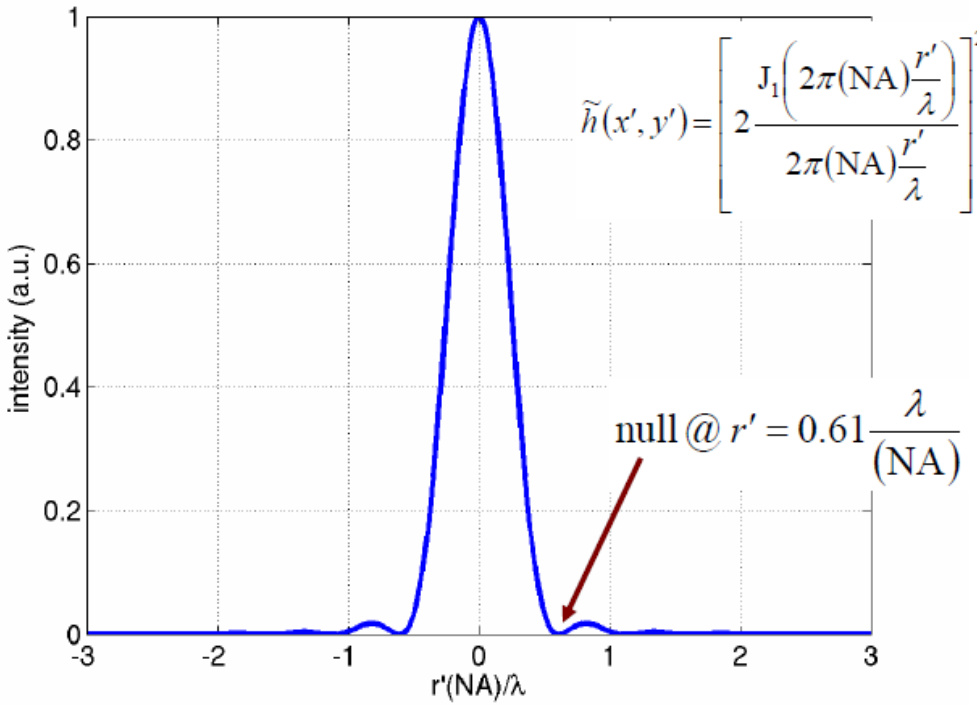
Optical System PSF

- The spatial response of an optical system is described by its Point Spread Function (PSF) $h(x, y)$
  - Analogous to the impulse response $h(t)$ of dynamic systems

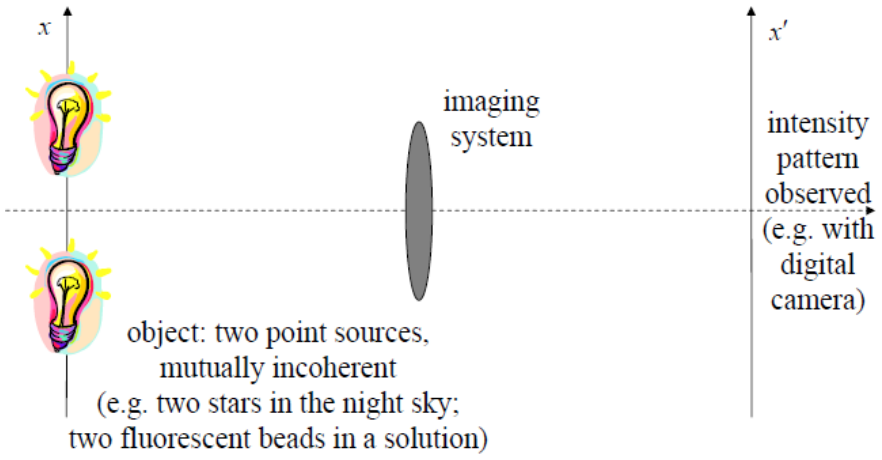


$$\tilde{h}(x',y') = \left[2\frac{J_1\left(2\pi(\mathrm{NA})\frac{r'}{\lambda}\right)}{2\pi(\mathrm{NA})\frac{r'}{\lambda}} \right]^2$$

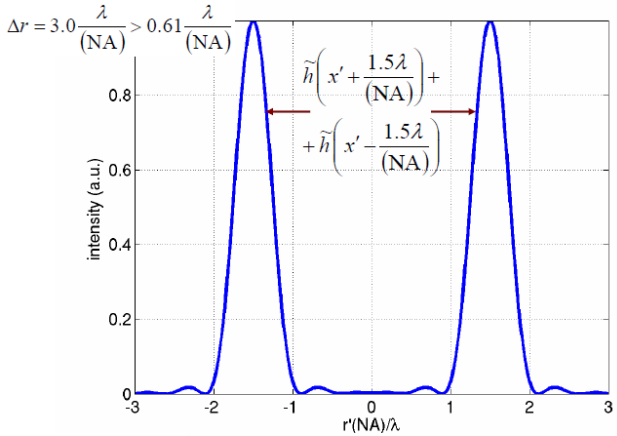
Images by G. Barbastathis, MIT

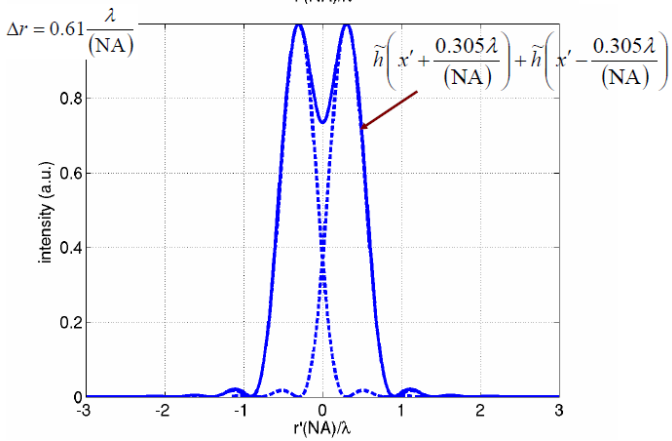
Optical Resolution

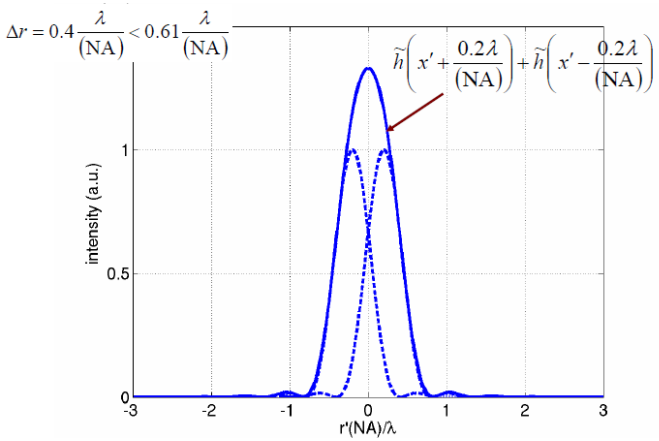
- Minimum distance Δr, where 2 point sources can be resolved by an optical system



$$\Delta r = 0.61\frac{\lambda}{(\mathrm{NA})}$$







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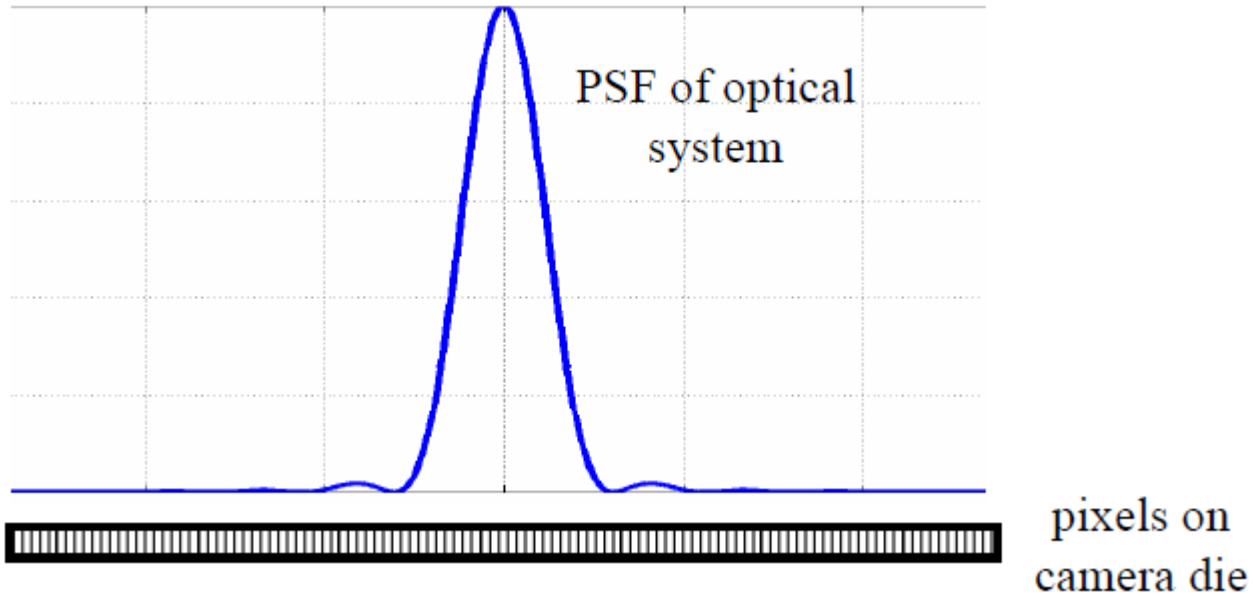
Optical Resolution

$$\Delta r = 0.61 \frac{\lambda}{(\mathrm{NA})}$$

- Resolution is proportional to light wavelength λ
  - Short-wavelength illumination (blue) results in better resolution
- Resolution is inversely proportional to Numerical Aperture (NA), a measure of light-collecting ability of optical system
  - Systems of smaller f# collect more light → smaller Δr
- For λ=0.5μm (green light) and NA=0.7 → Δr=0.508 μm
  - Optical resolution is on the order of 0.3 – 0.7 μm

Spatial Sampling

- The pixel size of the sensor defines spatial sampling of PSF
- The quality of the acquired image depends on both the optical system (PSF) and the camera (pixel size)



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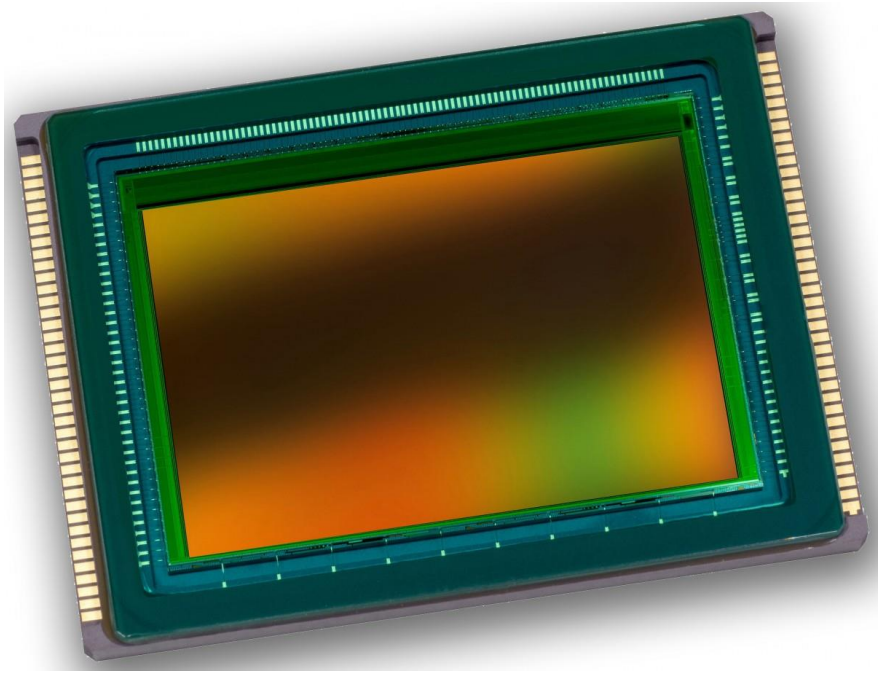
Spatial Sampling

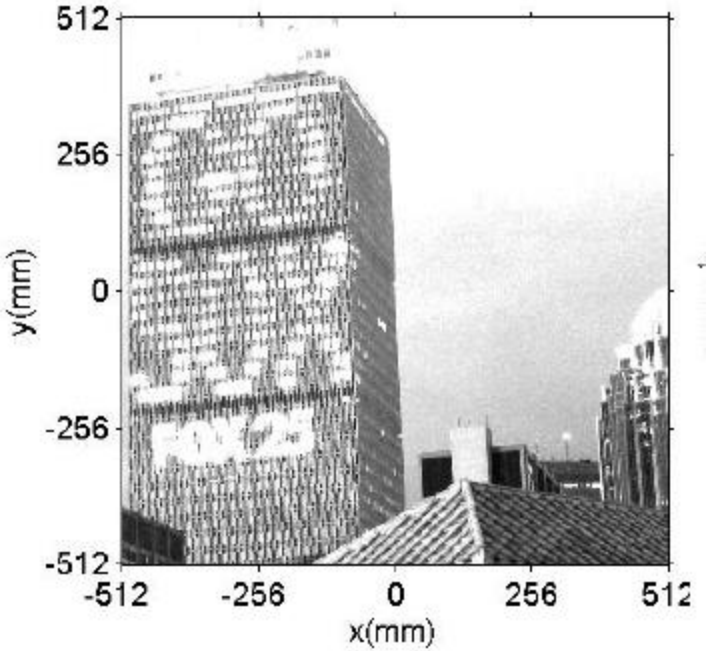
- Example: a CMOS detector



Parameter		Typical Value
Optical format		1/4-inch
Active pixels		1280(H) x 800(V) (entire array)
Pixel size		3.0 μm x 3.0 μm
Color filter array		RGB Bayer, Monochrome
Shutter type		Electronic rolling shutter and GRR
Input clock range		6 – 50 MHz
Output clock maximum		148.5 Mp/s (4-lane HiSPi) 74.25 Mp/s (Parallel)
Output	Serial	HiSPi, 12-bit
	Parallel	10-, 12-bit
Frame rate	720p	60 fps
Responsivity		4.0 V/lux-sec
SNR_{MAX}		41 dB
Max Dynamic range		Up to 79 dB
Supply voltage	I/O	1.8 or 2.8 V
	Digital	1.8 V
	Analog	2.8 V
	HiSPi	0.3 V - 0.6 V, 1.7 V - 1.9 V
Power consumption (typical)		326 mW (Linear Mode 1280x720 60 fps)
Operating temperature (ambient) -T_A		−30°C to + 70° C
Package options		9x9mm 63-ball iBGA

Fourier Optics

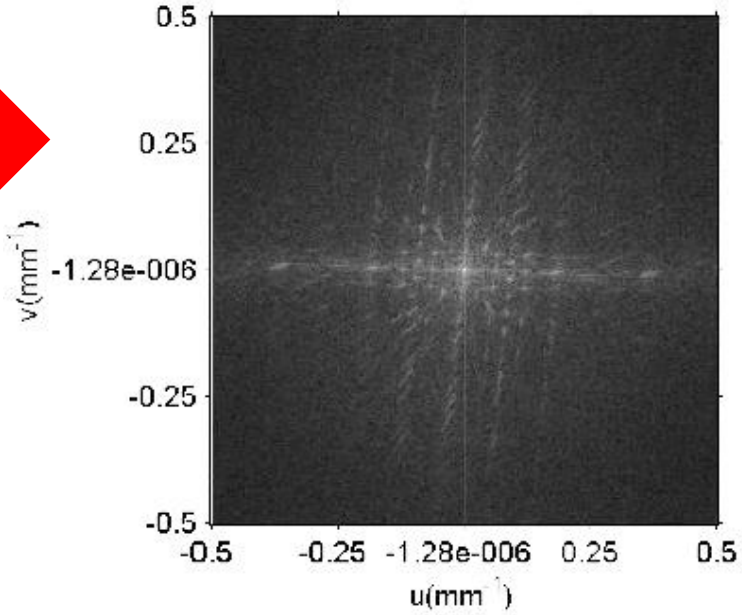
- Light intensity at any plane can be expressed in the 2D Fourier Domain



space domain

$g(x, y)$

F.T.



Fourier domain

(aka spatial frequency domain)

$G(u, v) = \Im\{g(x, y)\}$

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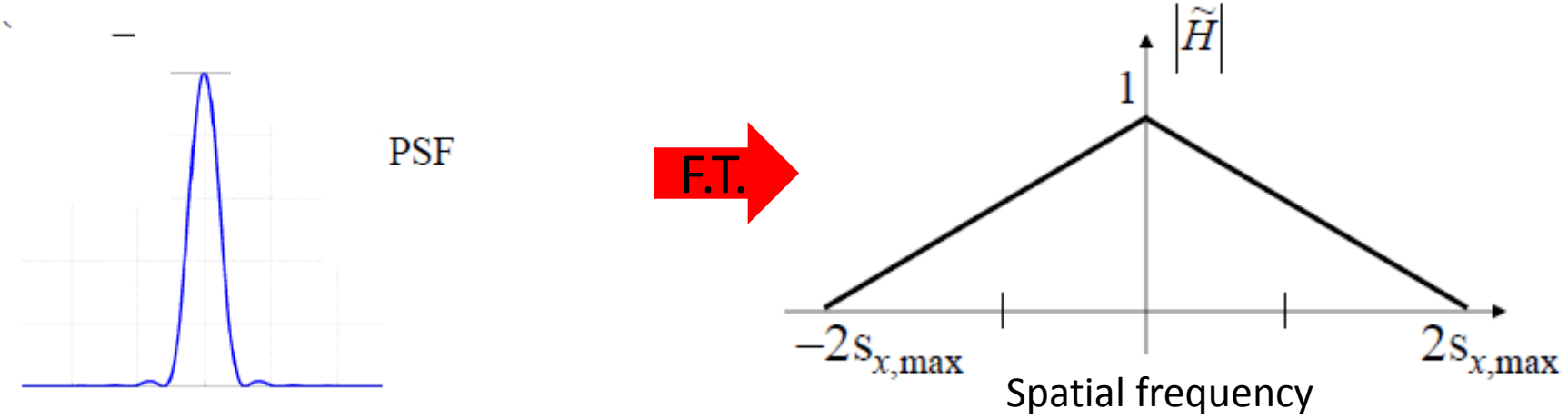
Fourier Optics

- The Fourier transformation of the PSF defines the system's modulation transfer function (MTF)
  - Corresponding of frequency response of dynamic systems
  - Real optical systems act as Low-Pass Filters (blurring)



Images by G. Barbastathis, MIT

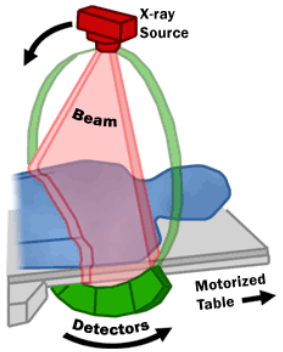
Examples of Optical Systems in Biomedical and Medical Imaging

- **Microscopes**

- **Endoscopes**

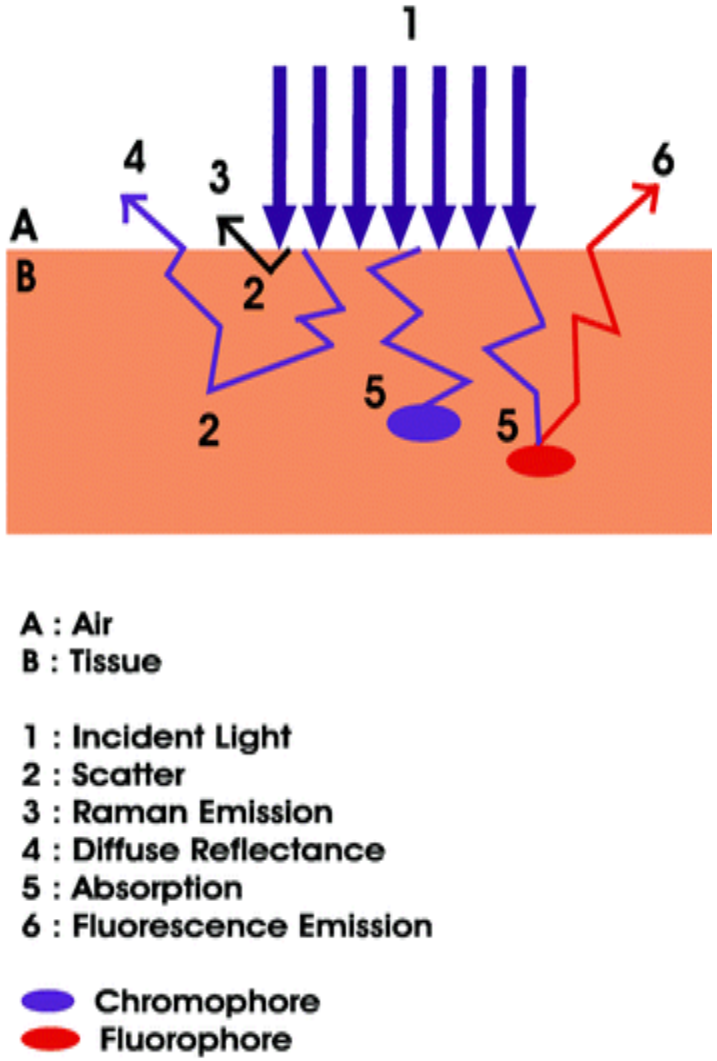
- **Goggles**

- **Tomography instruments**



Light-Tissue Interactions

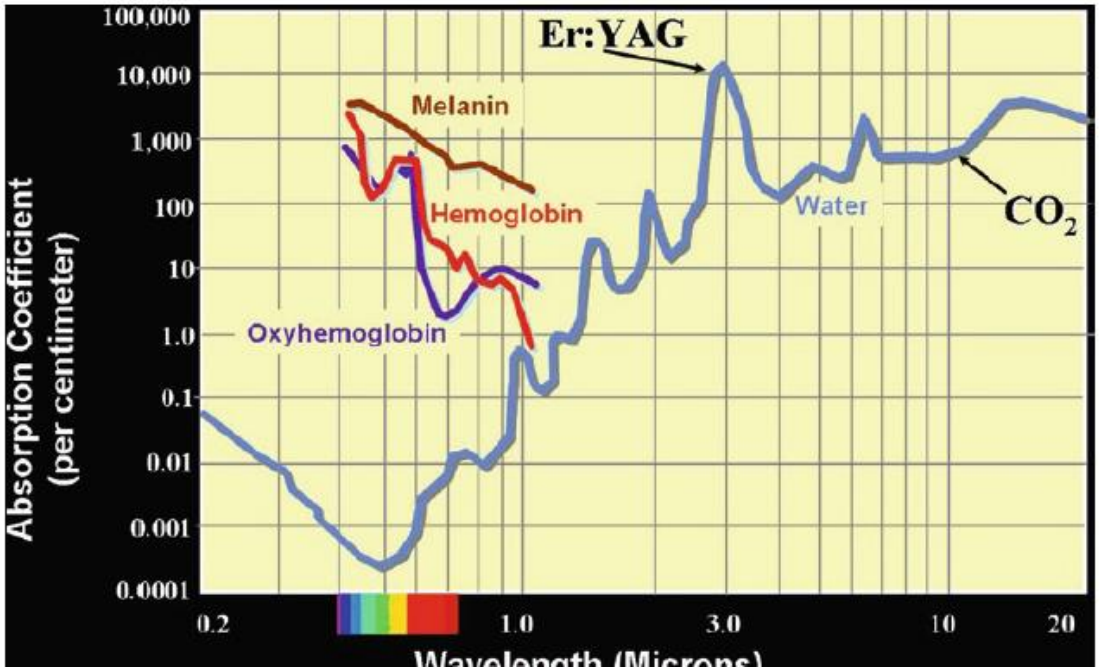
- Absorption (απορρόφηση)
- Scattering (σκέδαση)
- Both phenomena limit light penetration depth to a few hundred μm



Light paths of photons that highlight various light-tissue interaction phenomena (http://www.rsc.org/)

Light-Tissue Interactions

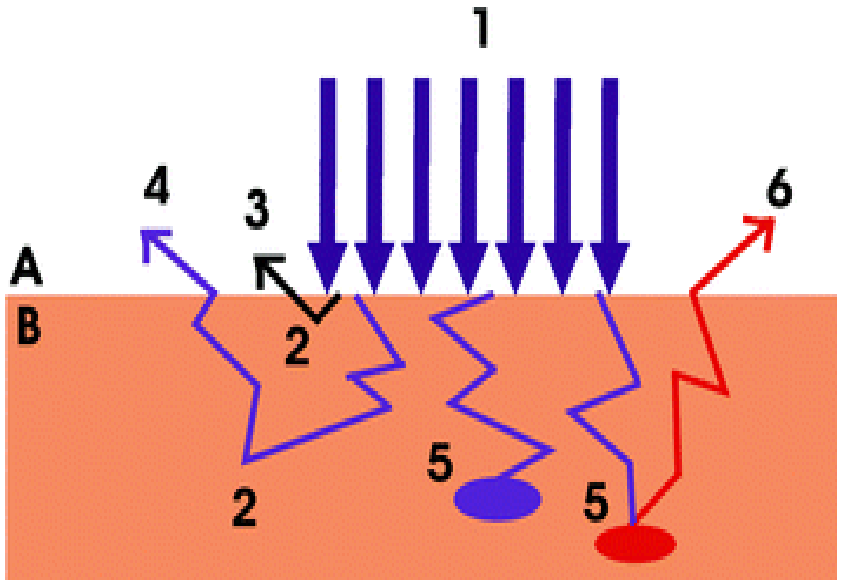
- Absorption of light by various tissue elements
  - Mechanism: A molecule absorbs a photon, gets excited → excess energy is coverted to heat when molecule returns to ground state
  - Each absorbing element absorbs light in specific wavelengths (described by its absorption spectrum)



Absorption spectra of various skincomponents (Lumenis Corp)

Light-Tissue Interactions

- Light scattering
  - Photons “bounce” on tissue elements and change direction
  - Depends on λ^{-4}: short wavelength light is scattered much more compared to IR
  - Hard to model analytically



Summary

- Light refers to the EM spectrum in the visible range
- Light can be described as a wave or as a set of particles (photons)
- Imaging systems (sets of lenses, mirrors, etc) map the object plane on the imaging plane (sensor)
- Imaging systems can be studied using geometric optics, diffraction theory, or Fourier optics
- The optical resolution of an optical system is defined by its PSF (equivalently by its MTF)
- Light interacts with tissues mainly by absorption & scattering
  - Light imaging is within ~0.5 mm from tissue surface